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DIGITAL STANDARDS CONVERSION: comparison of colour decoding methods

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Research Department, Engineering Division
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Summary

A number of PAL and NTSC decoding methods, several of which involve comb filters based on line delays, are compared, primarily for use in standards conversion. To simplify comparisons, the circuits are all converted into a general form consisting of a chrominance-pass filter, a subtractor used to obtain luminance and a chrominance demodulator. The theoretical performance of each circuit is summarised as a set of vertical frequency characteristics which show luminance and chrominance resolution, cross-luminance and cross-colour and, where present, other crosstalk and aliasing effects. In addition, practical impressions of the performance of each method have been obtained from a fully digital decoder using line-locked sampling and switched filters.

The optimum PAL decoding arrangements for direct viewing, for subsequent recoding to PAL and for standards conversion are all found to be different. For direct viewing, a two-line luminance circuit with nulls to reject subcarrier components, combined with a two-line version of the conventional delay line chrominance circuit produces the most acceptable pictures. For applications in which decoded signals are to be encoded as PAL subsequently, the complementary Weston circuit using two line delays is the most suitable of those tested. However, the degree of chrominance-luminance separation obtained is unlikely to be adequate for the circuit to be used as an imput to component signal processing equipment in studios. In a standards converter, the vertical-temporal filtering action of the interpolator can be designed to have a beneficial effect, suppressing cross-effects and other impairments left by the decoder. Because of this, the combination of a two-line luminance comb filter and simple chrominance demodulation retains good spatial resolution and, after the interpolator, achieves a low level of cross-effects. A similar arrangement is also found to be satisfactory for NTSC signals.

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COMPARISON OF COLOUR DECODING METHODS

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1. INTRODUCTION

1.1. Standards conversion

The exchange of television programmes between countries is complicated by differences in the line and field scanning rates used: in Europe, most television systems use 625 lines per picture and 50 fields per second with either PAL or SECAM colour coding; North America and Japan, however, use 525 lines per picture and 60 fields per second, with the NTSC system of colour coding. Programmes can be converted from one standard to another by transferring the picture information from the lines and fields of the input standard to those of the output standard. Suitable picture information for the output standard signal is obtained by interpolating between the lines and fields of the input standard signal. As interpolation consists of storage and arithmetic, the process is well-suited to digital implementation.

Digital interpolation in a standards converter is considerably simplified if line-locked sampled luminance and colour difference signals (Y, U and V) are processed. A line-locked sampling frequency produces an orthogonal sampling grid, in which samples on the current line fall directly beneath those on the previous line and field and exactly overlay samples on the previous picture. An orthogonal structure allows the interpolation process to operate on the vertical and temporal components in the signal without affecting horizontal components. In addition, the use of baseband colour difference signals avoids the complicated vertical and temporal structure of modulated chrominance signals.

1.2. Colour decoding for standards conversion

1.2.1. Sampling frequencies

Colour decoding can also benefit from the use of digital methods, particularly in the respects of performance stability and the accuracy of filter characteristics. If the luminance and colour difference signals for interpolation are to be obtained from a digital decoder, it is convenient to make the sampling frequency used in the decoder simply related to the sampling frequencies used in the interpolator.

For PAL signals, sampling at four-times the colour subcarrier frequency ($4f_{sc}$) would yield a nearly orthogonal structure. Also, by relating the sampling phase to the subcarrier reference phase, the chrominance signals would be partly demodulated by the sampling process. However, the sampling frequency (17·73 MHz) is too high to result in a conveniently low multiplexed YUV rate. Furthermore, there is a wide disparity between four-times subcarrier frequency in the PAL and NTSC systems, so that horizontal interpolation would be required to convert the number of active line samples between the two standards. Another disadvantage of subcarrier-locked sampling is that it depends on the mathematical relationship between the subcarrier frequency and the line rate being preserved exactly. If non-mathematical PAL signals were encountered, then the sampling structure would follow the subcarrier and orthogonality would be lost. As a result, picture information would slip sideways and interpolation would modulate the horizontal frequency response.

In comparison, a line-locked sampling frequency makes the colour demodulation process more complicated, but this is outweighed by a number of advantages. Firstly, an orthogonal structure can be obtained with a much lower sampling frequency, thus resulting in a conveniently low multiplexed YUV rate. Secondly, it is possible to choose line-locked sampling frequencies on the 625- and 525-line standards in which the number of active line samples is the same for each, so avoiding the need for horizontal interpolation. Also, because the sampling and colour demodulation processes are separate, non-mathematical signals can be accepted.

1.2.2. Chrominance–luminance separation

The methods of colour signal coding used in both the PAL and NTSC colour systems cause the chrominance and high-frequency luminance components of the signal to share a common frequency band. Because of this, when the signals are decoded, some luminance signals are incorrectly decoded as colour signals and some chrominance signals remain in the luminance channel. These crosstalk signals are referred to as cross-colour and cross-luminance respectively.

In standards conversion, the presence of crosstalk signals is particularly unwelcome because the converted signals are recoded, usually on a different colour system. Then the crosstalk components from the first decoding are also recoded and may cause more objectionable effects when decoded on the new standard. In any case, the crosstalk components from the first decoding process will be added to the normal crosstalk components of the second decoding.

Although the problem cannot be solved completely at the decoder, some improvement can be obtained by using more elaborate filters. These are used to separate more accurately the bands of frequencies containing predominantly chrominance signals and luminance signals. This is achieved by combining the conventional horizontal filtering methods with vertical filtering (sometimes known as comb filtering) in which signal contributions from more than one line are used. In addition, filtering in the decoder can have a beneficial effect by removing certain true luminance and chrominance components which would otherwise cause crosstalk in the second decoder.

1.3. Improved decoding methods

Prior to the work described in this Report, several new decoding methods using line delays had been suggested, both for standards conversion and for general use. These methods differed widely in their implementations; some used analogue methods exclusively,[1] some were digital, but depended on subcarrier-locked sampling,[2] and others required line-locked sampling.[3] During the course of the work, it was found that these methods could be generalised, to operate with either analogue or digital circuits and to use any super-Nyquist sampling frequency. It became apparent that, in their general forms, there were simple relationships between the methods. This has simplified the comparison of decoder performance.

In the following sections, the decoding process is divided into chrominance demodulation and chrominance–luminance separation. Demodulation and the related process of PAL modification are described for both continuous and sampled systems and this is followed by a tabulation of the filter characteristics for several methods of chrominance–luminance separation. Finally, the suitability of the separation filters is compared, both for standards conversion and for general use.

In a standards converter, the interpolator contributes to the overall performance of the equipment in a number of ways normally associated with the decoder, such as acting to reduce cross-luminance and cross-colour components left by the decoder. Because of this, the overall properties of the decoder–interpolator combination are dealt with in a separate report on interpolation.[4]

Much of the information on interpolation and colour decoding methods obtained from the experimental converter has been incorporated, by Designs Department, in the design of two new converters[5] for use in the Television Service.

2. COLOUR DECODING

2.1. A general form of decoder

Any method of colour decoding comprising filtering and demodulation can be converted to the general form of Fig. 1(a). This shows a chrominance separator consisting of a chrominance-pass filter followed by a chrominance demodulator, and a luminance separator in which chrominance from a chrominance-pass filter is subtracted from the composite signal to leave luminance. The use of separate chrominance-pass filters allows for systems in which the luminance and chrominance characteristics are non-complementary. For complementary systems, the general form can be simplified to that of Fig. 1(b), which is characterised only by the chrominance filter. Therefore, any method of chrominance separation forms the basis of a complementary method of luminance separation, and vice versa.

It is possible to arrange decoders into other general forms. For example, chrominance could be demodulated first and then followed by filtering of the baseband U and V signals. Alternatively, a general form could be based on luminance-pass filters instead of the chrominance-pass filters shown in Fig. 1. In each case, functionally equivalent operations could be performed. However, the arrangements of Fig. 1 are preferred because practical realisations based on these diagrams usually result in simplified circuitry.

Chrominance-pass filters suitable for decoding can also be used in a coder. A general form of complementary coder is shown in Fig. 1(c). Here the filter operates to remove those luminance and chrominance components which, when decoded, would tend to produce cross-colour and cross-

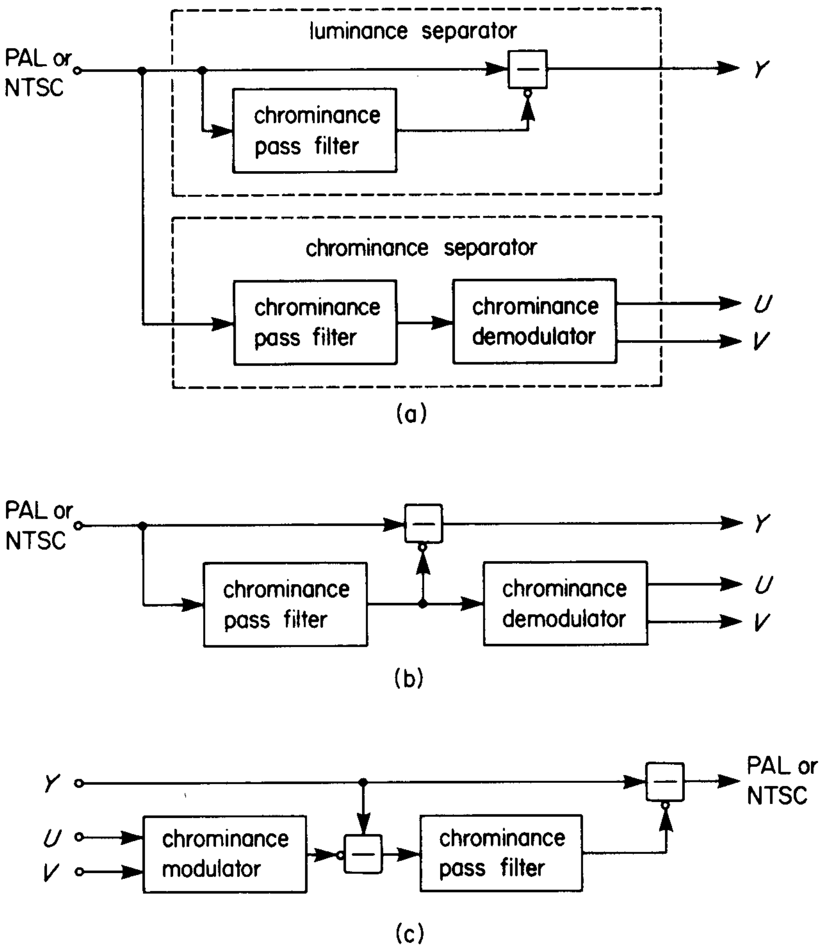

Fig. 1. General forms of decoder and coder: (a) a decoder with non-complementary luminance and chrominance separation filters, (b) a decoder with complementary filtering, and (c) a "clean" coder with complementary filtering

luminance, respectively. However, some loss of resolution in chrominance and high-frequency luminance is incurred.

2.2. Chrominance demodulation

The PAL and NTSC colour systems use suppressed-carrier amplitude modulation of quadrature subcarriers. The PAL chrominance signal can be represented mathematically as a function of time (t) by the expression:

$$U \sin \omega t \pm V \cos \omega t$$

in which U and V represent the modulating weighted colour difference signals and $\omega = 2\pi f_{sc}$. The sign of the V component alternates from one line to the next.

The colour information can be demodulated by multiplying the signal by appropriately phased subcarrier-frequency sine waves and low-pass filtering the resulting products. A PAL chrominance demodulator is shown in Fig. 2. U is obtained by multiplying by $2 \sin \omega t$ and V is obtained by multipling by $\pm 2 \cos \omega t$, as shown:

$$(U \sin \omega t \pm V \cos \omega t)\, 2 \sin \omega t$$

$$= U - U \cos 2\omega t \pm V \sin 2\omega t$$

$$(U \sin \omega t \pm V \cos \omega t)(\pm 2 \cos \omega t)$$

$$= V \pm U \sin 2\omega t + V \cos 2\omega t$$

In each case, the terms at twice subcarrier frequency are removed by low-pass filters so that U and V signals remain at the demodulator outputs.

Similarly, the NTSC chrominance signal,

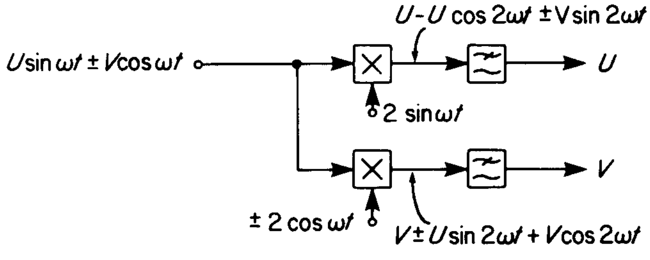

Fig. 2. A PAL chrominance demodulator

represented by the expression:

$$Q \sin \omega t + I \cos \omega t$$

can be demodulated by multiplication by 2 sin ωt and 2 cos ωt and low-pass filtering the resulting products. However, as Q is a low bandwidth (0·5 MHz) double sideband signal and I is a wideband (1·3 MHz) asymmetrical sideband signal, the Q and I low-pass filters must be different. The filtered Q and I components can then be converted to U and V according to the following equations:

$$U = Q \cos 33^\circ - I \sin 33^\circ$$

$$V = Q \sin 33^\circ + I \cos 33^\circ$$

The demodulation process is shown in spectral terms in Fig. 3. Fig 3(a) represents the baseband spectrum of an analogue video signal with chrominance information in the shaded region around the colour subcarrier frequency, whilst Fig. 3(b) represents the spectrum of the subcarrier frequency sine wave used for demodulation. Convolution of these two spectra (equivalent to multiplication in the time domain) produces the spectrum of Fig. 3(c) in which the baseband video spectrum has been shifted to be centred on f_{sc} and $-f_{sc}$. Therefore, the baseband chrominance information can be separated from the low frequency luminance centred on f_{sc} and the chrominance centred on $2f_{sc}$ by a low pass filter. This shows that horizontal bandpass filtering of the chrominance components before demodulation is unnecessary.

In a sampled system, the process is similar except that the baseband spectra of Fig. 3 are repeated around harmonics of the sampling frequency. This is shown in Fig. 4 for a sampling frequency (f_s) slightly less than $3f_{sc}$. The convolved spectrum Fig. 4(c) is shown in two parts for clarity; the upper spectrum shows the terms centred on zero frequency, whilst the lower spectrum shows the terms centred on f_s and $-f_s$. Alternatively, the spectrum of Fig. 3(c) can be considered to be folded back onto itself where it exceeds half the sampling frequency, as shown in Fig. 4(d).

The spectra of Fig. 4 can be used to examine the onset of aliasing as the sampling frequency is reduced. For System I PAL, the onset of serious aliasing in the demodulated signal, Figures 4(c) and 4(d), due to chrominance components centred on $f_s - 2f_{sc}$, coincides with the onset of aliasing in the original spectrum Fig. 4(a). Therefore, this method of demodulation can be used with any sampling frequency above the Nyquist rate. For NTSC, however, useful chrominance components extend at least 0·7 MHz further in the lower sideband than in the upper sideband, because the I signal spectrum is asymmetrical.* Therefore, aliasing in the demodulated spectrum will occur before aliasing in the original spectrum so a higher than normal sampling frequency is required. For standards conversion, it is convenient to use roughly similar sampling frequencies for PAL and NTSC signals in order to simplify the conversion of active-line length. Because of this, the NTSC signal is sampled considerably above the Nyquist rate, so that aliasing in a digital demodulator will not occur.

2.3. PAL modifiers

Vertical filtering involves combining contributions from several lines. In PAL chrominance signals, however, the phase structure of the U and V subcarriers alters from one line to the next. This is because the reference subcarrier phase changes by approximately 90° over one line period and the V subcarrier is inverted on alternate lines. Therefore, to obtain a satisfactory vertical filtering action for modulated chrominance signals, it is necessary to convert the individual contributions in the filter to a common phase.

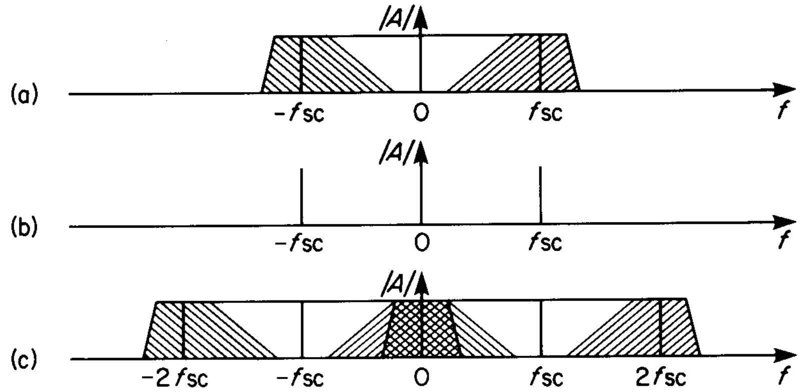

Fig. 3. Frequency spectra for chrominance demodulation: (a) the spectrum of an analogue video signal with chrominance information in the shaded region around the colour subcarrier frequency, (b) the spectrum of a subcarrier frequency sine wave, and (c) the result of convolving (a) and (b)

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* This argument also applies to Systems B and G PAL.

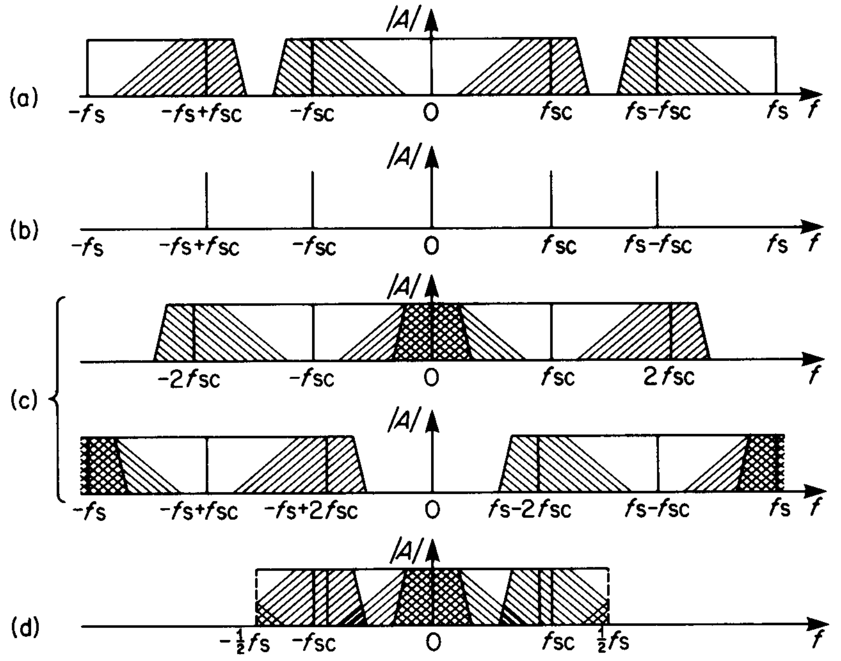


Fig. 4. Frequency spectra for digital chrominance demodulation: (a) the spectrum of sampled video signals, (b) the spectrum of a sampled subcarrier frequency sine wave, (c) the convolved spectrum showing components from zero frequency and $\pm f_s$ separately, and (d) the full convolved spectrum

This problem could be avoided by demodulating the chrominance to produce baseband U and V signals which could then be filtered without the complication of subcarrier modulation. However, this has two disadvantages: first, two separate filters would be required for the U and V channels; and secondly, the filtered U and V signals would have to be re-modulated, so that the filtered chrominance could be subtracted from the composite signal to obtain luminance. It is preferable, therefore, to operate on the modulated chrominance contributions directly.

The conversion of subcarrier phase and V-switch sense is obtained using a PAL modifier. This consists of a multiplier fed with a twice subcarrier frequency sine wave, followed by a chrominance band-pass filter, as shown in Fig. 5. The phase of the twice subcarrier frequency sine wave relative to the reference phase of the PAL signal determines the phase shift in the modified signal. For example, if a PAL chrominance signal represented by:

$$U \sin \omega t \pm V \cos \omega t$$

is multiplied by $-2\cos 2\omega t$ then there is no shift of the reference phase, but the V-switch sense is inverted, as shown:

$$(U \sin \omega t \pm V \cos \omega t)(-2\cos 2\omega t)$$

$$= U \sin \omega t \mp V \cos \omega t - U \sin 3\omega t \mp V \cos 3\omega t$$

The terms at three-times subcarrier frequency are removed by the chrominance bandpass filter.

Alternatively, if $2\sin 2\omega t$ is fed to the multiplier, then a 90° phase shift is produced as well as the V-switch inversion:

$$(U \sin \omega t \pm V \cos \omega t)(2 \sin 2\omega t)$$

$$= U \cos \omega t \pm V \sin \omega t - U \cos 3\omega t \pm V \sin 3\omega t$$

$$= U \sin(\omega t + 90^\circ) \mp V \cos(\omega t + 90^\circ)$$

$$- U \cos 3\omega t \pm V \sin 3\omega t$$

Again, the terms at three-times subcarrier frequency are removed by the chrominance band-pass filter.

The action of a modifier is shown in spectral terms in Fig. 6. Fig. 6(a) represents the baseband spectrum of an analogue video signal with chrominance information in the shaded region around the colour subcarrier frequency and Fig. 6(b) represents the spectrum of the twice subcarrier frequency sine wave used in the modifier. Convolving these spectra produces the result shown in Fig. 6(c) in which the chrominance information from f_{sc} is shifted to $-f_{sc}$ and that from $-f_{sc}$ is shifted to f_{sc}.

If the same operations were performed in a sampled system, the resulting spectrum would be

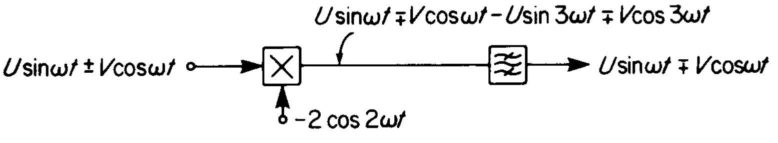


Fig. 5. A PAL modifier

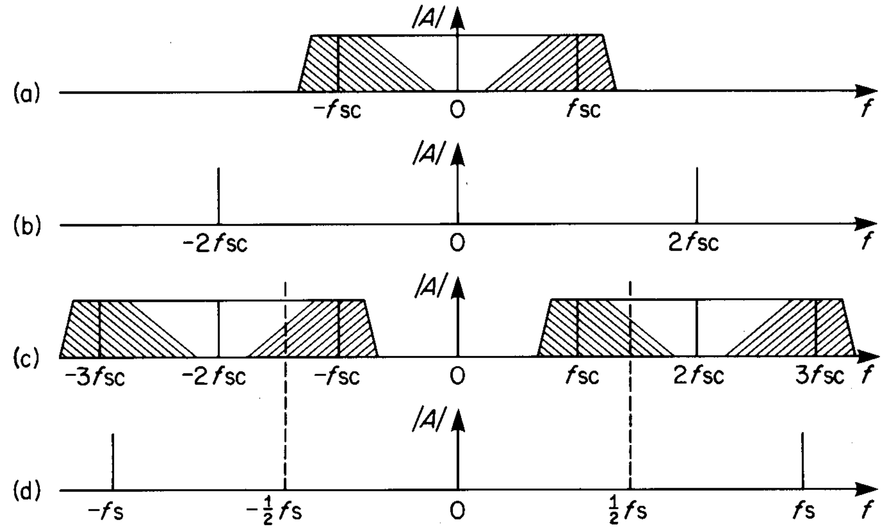
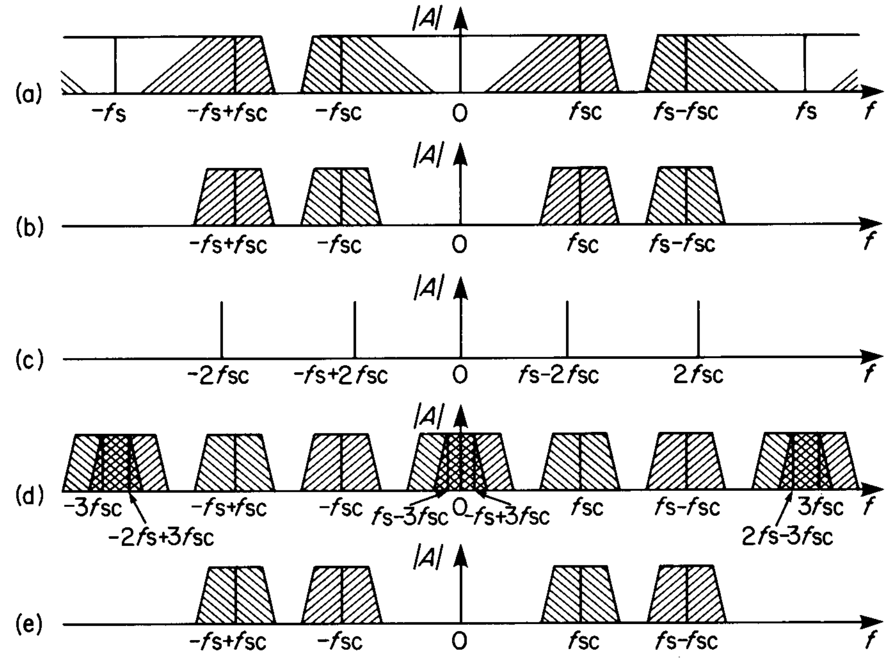


Fig. 6. Frequency spectra for PAL modification: (a) the spectrum of a composite video signal, (b) the spectrum of the twice subcarrier frequency sine wave used in the modifier, and (c) the result of convolving (a) and (b). The positions of the sampling frequency and the half sampling frequency are shown relative to components in the modified spectrum in (d)

that of Fig. 6(c) folded back for frequencies above half the sampling frequency. The positions of the sampling frequency and the half sampling frequency are shown relative to the modified spectrum in Fig. 6(d). Although the required chrominance modification would have been achieved, aliased low frequency luminance signals centred on $2f_{sc}$ in Fig. 6(c) would occupy the same band as chrominance at f_{sc}. For sampling frequencies at or near to $3f_{sc}$ this can be avoided by inserting a chrominance bandpass filter before the multiplier. Fig. 7 shows the repeated spectra of a modifier system, including prefiltering, for a sampling frequency slightly less than $3f_{sc}$. Fig. 7(a) shows the spectrum of the sampled video signal, whilst in Fig. 7(b) the low frequency luminance has been removed by the chrominance bandpass filter. When the spectrum of Fig. 7(b) is convolved with the sampled twice subcarrier frequency sine wave, Fig. 7(c), the modified spectrum of Fig. 7(d), is produced. Finally, the unwanted products can be removed by a chrominance bandpass filter to leave the modified spectrum as shown in Fig. 7(e).

The lower limit of sampling frequency for correct operation of the modifier is again the Nyquist rate, as shown for the PAL demodulator. However, for sampling frequencies near to $4f_{sc}$, the aliased chrominance signals centred on f_s–$3f_{sc}$ will interfere with the wanted chrominance signals centred on f_{sc}. This places an upper limit on the sampling frequency.



(a) the spectrum of sampled video signals, (b) the spectrum of sampled video chrominance signals obtained by band-pass filtering, (c) the spectrum of a sampled twice-subcarrier frequency sine wave, (d) the result of convolving (b) and (c), and (e) the spectrum of PAL modified chrominance obtained by band-pass filtering (d)

Fig. 7. Frequency spectra for a digital PAL modifier operating at a sampling frequency slightly less than three-times subcarrier frequency

Although it is unnecessary in the present application, this upper limit can be avoided by using two filters, one with zero phase shift and one with 90° phase shift, preceding two multipliers fed with quadrature $2f_{sc}$ waveforms. When the outputs of the multipliers are added together, the unwanted components centred on $f_s - 3f_{sc}$ are in antiphase and so are cancelled. Consequently, no post-filter is required with this method since the unwanted terms shown in Fig. 7(d) are not present. This technique is sometimes used for the generation of SSB signals.[8]

2.4. Generalising decoder circuitry

Previously, many of the techniques and configurations used in decoders have resulted from the constraints of analogue or digital technology. Because of this, samplers and PAL modifiers have been used to obtain the same effect and delays have been used as a convenient means of obtaining phase shifts.

However, the use of expedient techniques often conceals the true operation of a decoder circuit and this hinders the comparison of performance between methods based on different technologies. When circuits are converted to the general form, shown in Fig. 1(b), and the correct processes are substituted for the expedient, relationships between the circuits are revealed which are not apparent in their original forms. Furthermore, in their general forms, the methods can be implemented as analogue circuits or as digital circuits with a wide range of sampling frequencies. Therefore, the choice of a particular decoding method no longer dictates which technology is to be used.

The advantages of the general form can be illustrated by comparing the conventional PAL delay line chrominance circuit, Fig. 8(a), with its general form, Fig. 8(b). The difference between the two circuits lies in the methods used to obtain co-phased chrominance contributions from across the line delay to feed to the demodulators.

In the conventional circuit, Fig. 8(a), the "line" delay is not exactly one line period, but is, instead, a whole number of half subcarrier periods, commonly 283½ or $284t_{sc}$. This small change in delay acts as a 90° phase shift at subcarrier frequency and so provides a simple phase relationship between the two ends of the delay. For a $284T_{sc}$ delay, the U subcarrier signals are co-phased, whilst V subcarrier signals are anti-phased because of the inversion of the V-switch sense from one line to the next. Thus, the low vertical frequency components of U and V can be separated by using an adder and a subtractor to feed the U and V demodulators, respectively. The high vertical frequency components of V, which pass through the adder with the low frequency U signals, are rejected by the phase discriminating property of the U channel synchronous demodulator. Similarly, high vertical frequency U components are suppressed by the V channel demodulator.

Although this use of a delay as a phase shift has adequate performance in practice, it is actually imperfect. This is because the phase shift of the delay

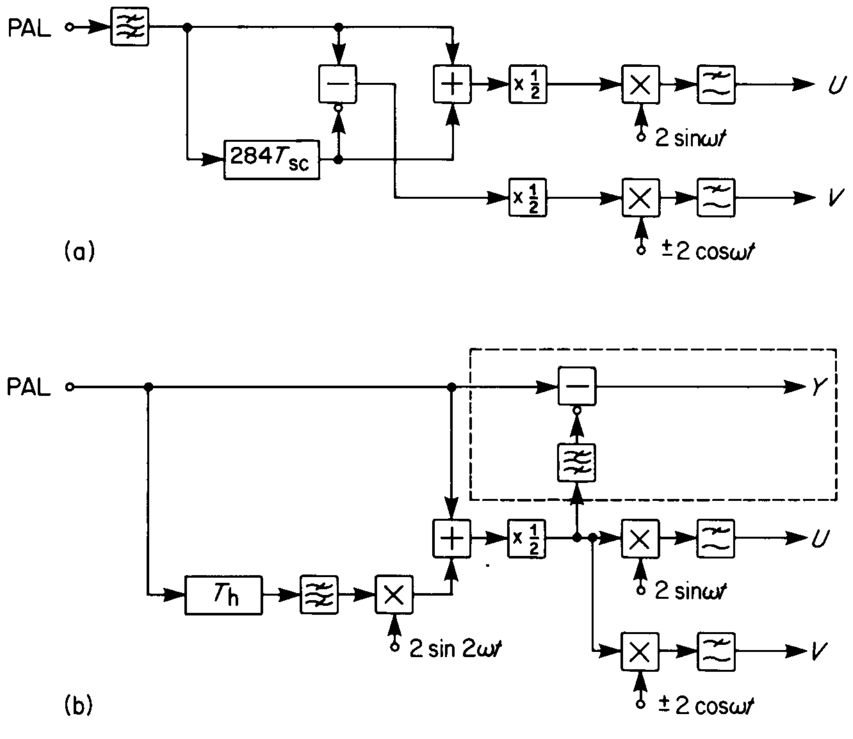


Fig. 8. (a) the conventional form of a delay line PAL chrominance circuit and (b) a generalised circuit which is functionally equivalent

is a function of frequency so that the subcarrier sidebands are not phase shifted by exactly 90°. This results in hue errors on vertical chrominance transitions, for example, on the edges of conventional vertical colour bars. An additional effect is that the frequency characteristic of the comb filter is diagonal, that is, partly vertical and partly horizontal, instead of being a purely vertical filter. This causes diagonal chrominance detail of one slope to be attenuated more than that of equal, but oppositely signed, slope. The correct method, therefore, would be to substitute a full line delay and a 90° phase shifter for the $284T_{sc}$ delay of Fig. 8(a).

The generalised circuit, Fig. 8(b) accordingly uses a full line delay, but instead of just using the 90° phase shifter, substitutes a PAL modifier. This has the dual purpose of providing an overall 90° phase shift and inverting the V subcarrier, so that the chrominance from the modifier is identically in phase with the input chrominance. The two signals can be combined, therefore, in a common averager and share a common path to the demodulators.

In itself, this alternative to the conventional arrangement is probably somewhat more complicated, requiring an extra multiplier for the modifier and only saving the subtractor. The real advantage lies in the convenience with which the circuit can be extended to provide a complementary luminance separation method, by the additional circuitry shown within the dashed outline in Fig. 8(b). This is possible because the vertically filtered chrominance at the demodulator input has the same phase and PAL switch sense as the direct composite signal. Therefore, the filtered chrominance can be used to cancel the chrominance in the composite signal to leave luminance. To obtain luminance by chrominance cancellation with the circuit of Fig. 8(a), it would be necessary to remodulate the demodulated colour difference signals, so requiring two more multipliers.

By considering the processes involved it can be shown that the combination of a demodulator and a remodulator can be replaced by a simpler circuit with equivalent performance. If the colour difference signals are remodulated in the same phase as they were demodulated, the circuit has the effect of a bandpass filter. However, if the phase of the V signal is inverted in the demodulation and remodulation process, then the effect is that of a PAL modifier. These equivalences, shown in Fig. 9 have been used extensively in the derivation of the general form of circuits described in the following section.

3. PAL CHROMINANCE–LUMINANCE SEPARATION CHARACTERISTICS

3.1. PAL decoders

Eight different methods of PAL decoding have been investigated for standards conversion. These are shown, rearranged to the general form of Fig. 1(b) in Fig. 10. The circuits range from the simple PAL decoder of Fig. 10(a) in which the coded signal is band-pass filtered and demodulated, to circuits using several line delays. These are used to filter vertical information in the signal in an attempt to obtain improved separation of chrominance and luminance. As shown, the methods differ only in their chrominance–luminance separation filters, since each circuit includes a simple PAL demodulator.

All the circuits have been instrumented digitally using line-locked sampling, although the four-line circuit, Fig. 10(h), was rejected at an early stage of development because of its poor performance. Alternatively, the circuits could use other sampling

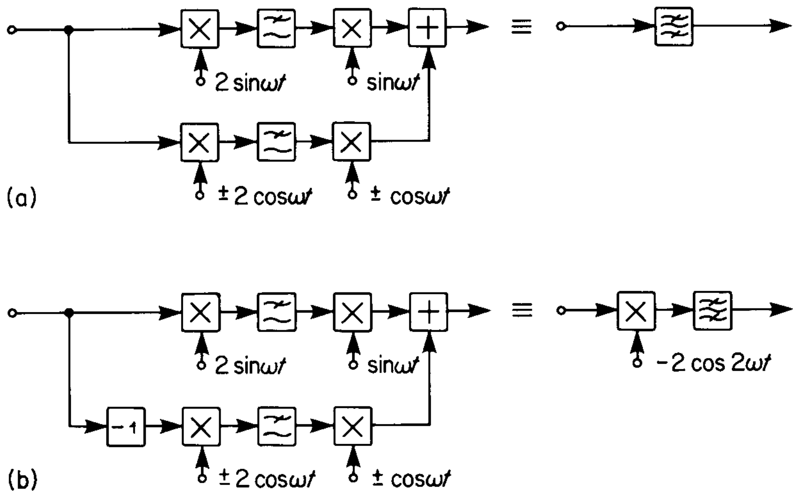


Fig. 9. The effect of decoding and recoding: (a) with remodulation in the same phase as demodulation and (b) with the V signal remodulated with the opposite phase to demodulation

frequencies or they could be instrumented in analogue form with equivalent theoretical performance. However, the stability and the well-defined frequency and phase characteristics of the digital circuits were particularly important in comparing the performance of the different methods.

The chrominance–luminance separation performance of each circuit can be summarised as a set of vertical frequency characteristics. There are eight curves describing each circuit, four for chrominance, shown in Fig. 11, and four for luminance, shown in Fig. 12. The abscissa of each curve represents a band of frequencies extending from one line harmonic to the next. Negative portions of the characteristics are shown as dashed lines. The general circuit of Fig. 1 is shown again in Fig. 13 marked with the positions at which the various response curves are taken.

3.2. Explanation of chrominance characteristics

Columns (i) and (ii) in Fig. 11 show the vertical frequency characteristics of each chrominance filter up to the demodulator input. Two sets of curves are shown because the response of the filter for signals in the *U* and *V* phases may differ if the filter includes a modifier. In the vertical frequency spectrum of modulated chrominance, the *U* and *V* subcarrier signals are centred on the $\frac{3}{4}$ and $\frac{1}{4}$ line-offset positions respectively. Therefore, in the first column of characteristics (Fig. 11(i)), for *U* phase signals, each curve has unity gain at the $\frac{3}{4}$ line-offset position (234 cycles/picture height). Similarly, the second column of curves (Fig. 11(ii)), for *V* phase signals, all have unity gain at $\frac{1}{4}$ line-offset (78 c/p.h.). In addition, these curves show the cross-colour performance of each circuit. Any luminance in the chrominance frequency band will be attenuated by these characteristics before being demodulated to produce cross-colour in the *U* or *V* outputs.

When the chrominance signals are demodulated, the spectrum is shifted from the chrominance band to the baseband and from the $\frac{3}{4}$ line-offset position (for *U*) or the $\frac{1}{4}$ line-offset position (for *V*) to the line harmonic position. Thus, the chrominance filtering and demodulation has the resultant effect on baseband chrominance signals shown in the third column of curves (Fig. 11(iii)), which apply similarly for *U* and *V*.

In most cases, this third curve is just a shifted version of the modulated chrominance characteristics, but in Figs. 11(iii), (f) and (g), this is not so. For these filters, the modulated chrominance curves are asymmetrical about the *U* and *V* subcarrier positions. As a result, the demodulated output curve, produced by averaging contributions from the upper and lower sidebands, has a different shape from the modulated chrominance curve. Additionally, because of the asymmetry, the demodulators are unable to separate *U* and *V* phase signals perfectly and there is crosstalk between the *U* and *V* signals, proportionate to the degree of asymmetry. Accordingly, the fourth column, Fig. 11(iv), shows the vertical frequency *U–V* crosstalk characteristics for the demodulated signals.

3.3. Explanation of luminance characteristics

The curves of Fig. 12 show the vertical frequency characteristics of each luminance filter over the chrominance band, that is, at frequencies near to 4·43 MHz. As with the chrominance curves, the inclusion of a modifier can lead to different characteristics for signals in the *U* and *V* phases. The first column of curves (Fig. 12(i)) shows the effect of the luminance filter for signals in the *U* phase, whilst the second column of curves (Fig. 12(ii)) applies for signals in the *V* phase. Therefore, these curves show directly the degree of suppression of cross-luminance from *U* and *V* chrominance signals. In particular, all the curves of Fig. 12(i) have zero response at the *U* subcarrier ($\frac{3}{4}$ line-offset, 234 c/p.h.) position, whilst the curves of Fig. 12(ii) all have zero response for the *V* subcarrier ($\frac{1}{4}$ line-offset, 78 c/p.h.) position.

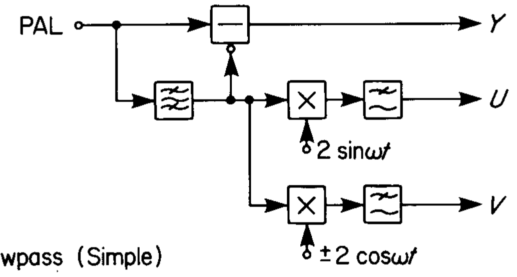
In some cases, the complementary relationship between the luminance and chrominance filters is readily apparent, as the curves of Fig. 12(i) and (ii) can be obtained by subtracting the corresponding curves of Fig. 11(i) and (ii) from unity. However, this is not so for Figs. 12(b) and (c) because, for the one-line delay filters, the relationship is complicated by phase response.

As an alternative to the characteristics for luminance signals in phase with the *U* and *V* subcarriers, Figs. 12(i) and (ii), the effect of the luminance filter can be expressed as a combination of true and aliased luminance characteristics. Thus, the curves in the third column, Fig. 12(iii), show the action of the filter for signals not affected by the modifier, whilst the characteristics for signals that pass through the modifier and are, therefore, aliased about twice subcarrier frequency, are shown in Fig. 12(iv). Although the true and aliased luminance characteristics are shown separately for clarity, both the filtered true luminance and aliased luminance signals would be present in the output. As the aliasing adds a temporal component, the aliased luminance alternately reinforces and cancels the true luminance.

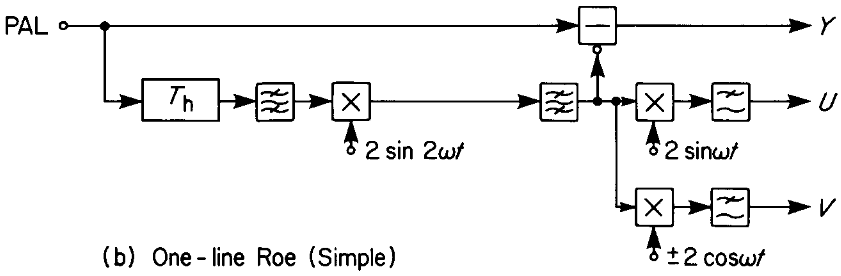
3.4 Decoder chrominance–luminance separation circuits

The decoders of Fig. 10 differ only in their vertical frequency characteristics, because the chrominance bandpass filter, the chrominance demodulator and the subtractor used to obtain luminance are common to all the circuits. In essence, as the circuits are complementary, each method represents a different division of the high frequency part of the spectrum into a luminance region and a chrominance region. As such, each is inevitably a compromise between retaining wanted information and rejecting crosstalk, because luminance and chrominance signals both extend throughout the shared band.

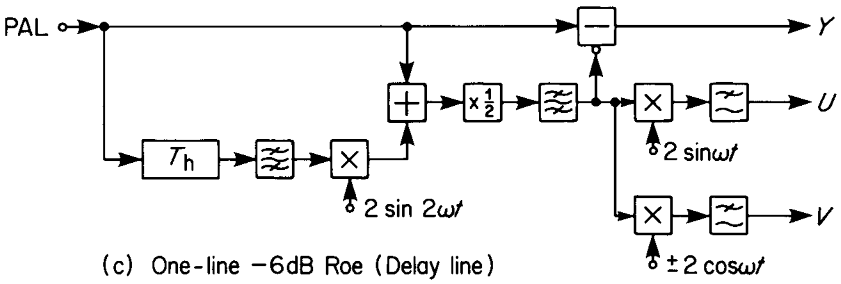
In the following descriptions, when the conventional forms of the luminance and chrominance circuits are known by different names, the first part



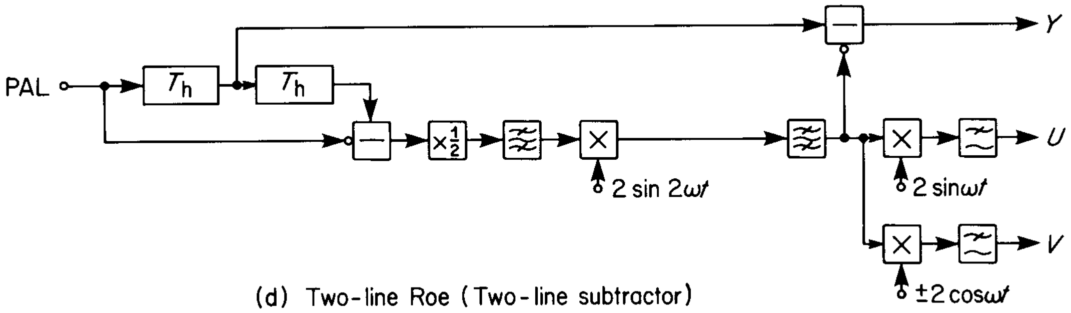
(a) Lowpass (Simple)



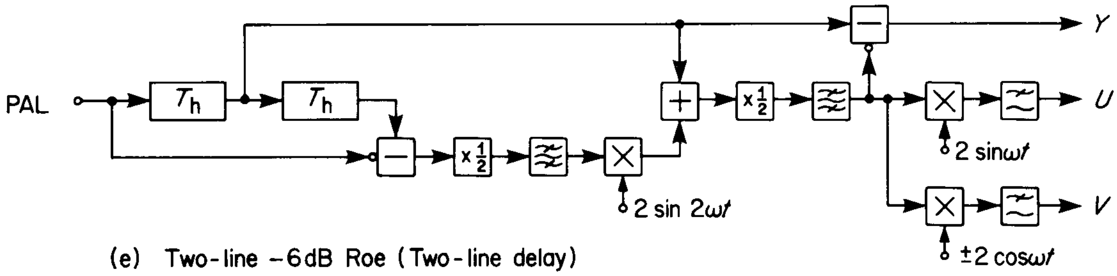
(b) One-line Roe (Simple)



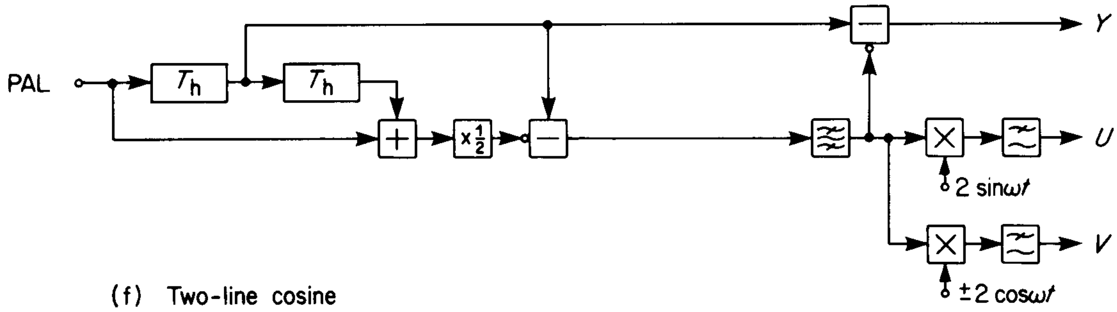
(c) One-line −6dB Roe (Delay line)



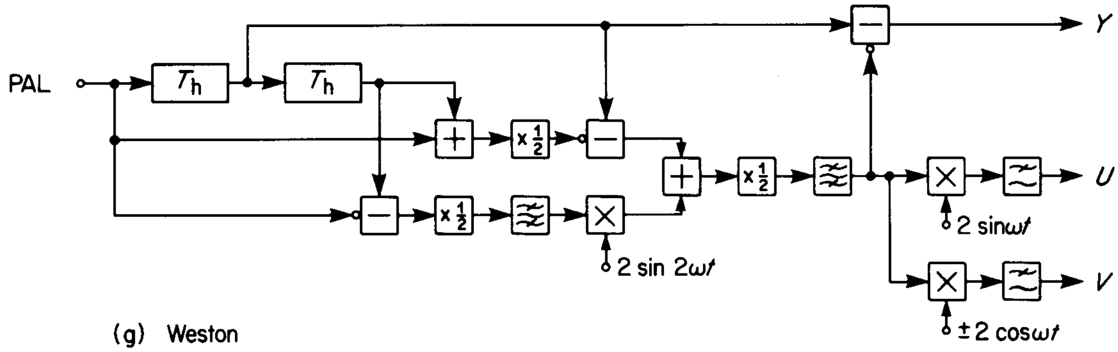
(d) Two-line Roe (Two-line subtractor)



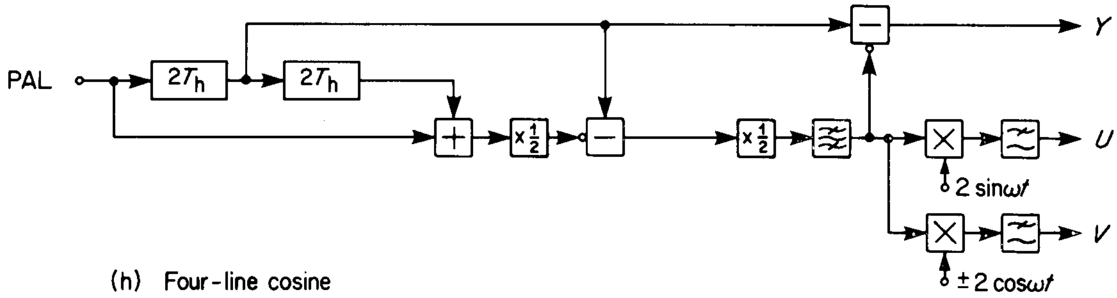
(e) Two-line −6dB Roe (Two-line delay)



(f) Two-line cosine



(g) Weston



(h) Four-line cosine

Fig. 10. PAL decoder circuits converted to the general form

of the sub-section title describes the luminance circuit and the second part, in parentheses, describes the chrominance circuit.

3.4.1. Low-pass (Simple)

This circuit, Fig. 10(a), treats the whole of the shared band, that is, frequencies above about 3 MHz, as chrominance. This is shown in the vertical frequency characteristics, Figs. 11(a) and 12(a). There is no loss of vertical chrominance resolution, Fig. 11(a)(iii), but consequently there is no suppression of cross-colour, Fig. 11(a)(i) and (ii). Also the line-to-line hue errors produced by differential phase distortion are unsuppressed; these errors appear as the 156 c/p.h. vertical pattern known as Hanover bars.

For luminance, the combined effect of the chrominance band-pass filter and the subtractor is

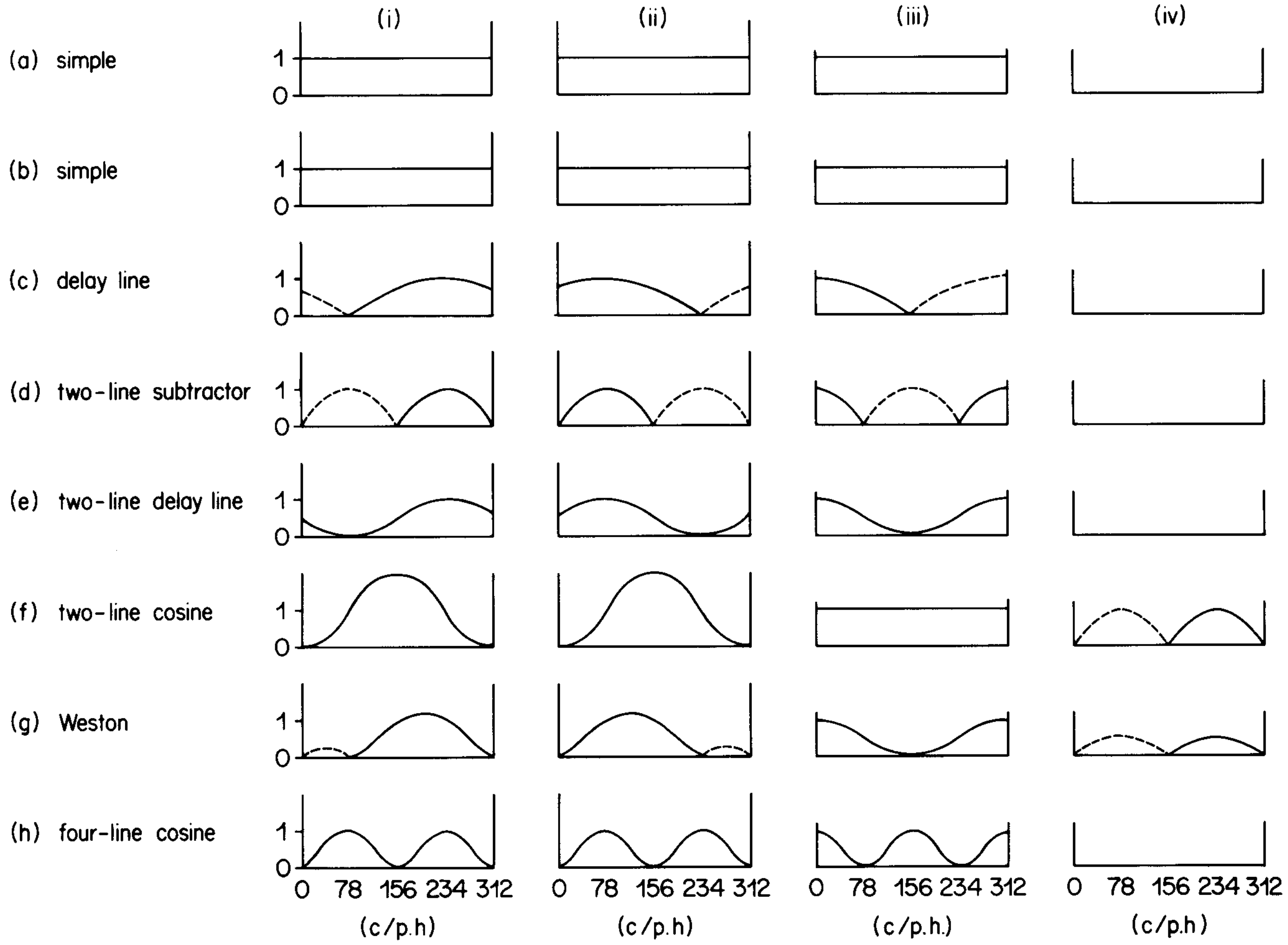


Fig. 11. Chrominance vertical frequency characteristics for the decoders of Fig. 10. The four curves for each decoder show: (i) *U*-channel modulated chrominance and cross-colour, (ii) *V*-channel modulated chrominance and cross-colour, (iii) *U* and *V* channel demodulated chrominance, and (iv) *U*-*V* crosstalk in demodulated chrominance.

equivalent to that of a low-pass filter; so there is very little impairment from cross-luminance (a small amount of cross-luminance remains from components below 3 MHz), but true luminance above 3 MHz is suppressed as well, Fig. 12(a). The loss of luminance and removal of cross-luminance with low-pass filtering is much greater than that produced by the luminance notch of a conventional PAL decoder.

3.4.2. One-line Roe (Simple)

The one-line Roe circuit for luminance, shown in Fig. 10(b), was originally evolved as a means of retaining more luminance than the conventional notch by making use of the output of the PAL delay line[1]. However, the one-line Roe luminance circuit and the delay line chrominance circuit (Section 3.4.3) described in Reference 1, are not a complementary pair.

The circuit uses a PAL modifier to adjust the phase and *V*-switch sense of chrominance signals from the previous line to be the same as those on the current line. For an area of constant colour, the chrominance signals from the two lines cancel in the subtractor to remove cross-luminance. If there is a colour change from one line to the next, the cancellation fails and cross-luminance remains at the transition.

For luminance signals, the modifier has the effect of producing a luminance alias, centred on twice subcarrier frequency. This delayed, aliased luminance is mixed with the direct, true luminance in the subtractor. The two components alternately reinforce and cancel one another at a frequency of 12½ Hz so that the signals at the luminance output require twice the range of normal luminance. Visually, the 12½ Hz beat frequency is only disturbing on high contrast signals.

As in the previous chrominance circuit, there is no loss of vertical chrominance resolution, nor is there any suppression of cross-colour or Hanover bars, Fig. 11(b). However, in this case, the chrominance is shifted by one field-line spacing down the picture so that luminance and chrominance are misregistered.

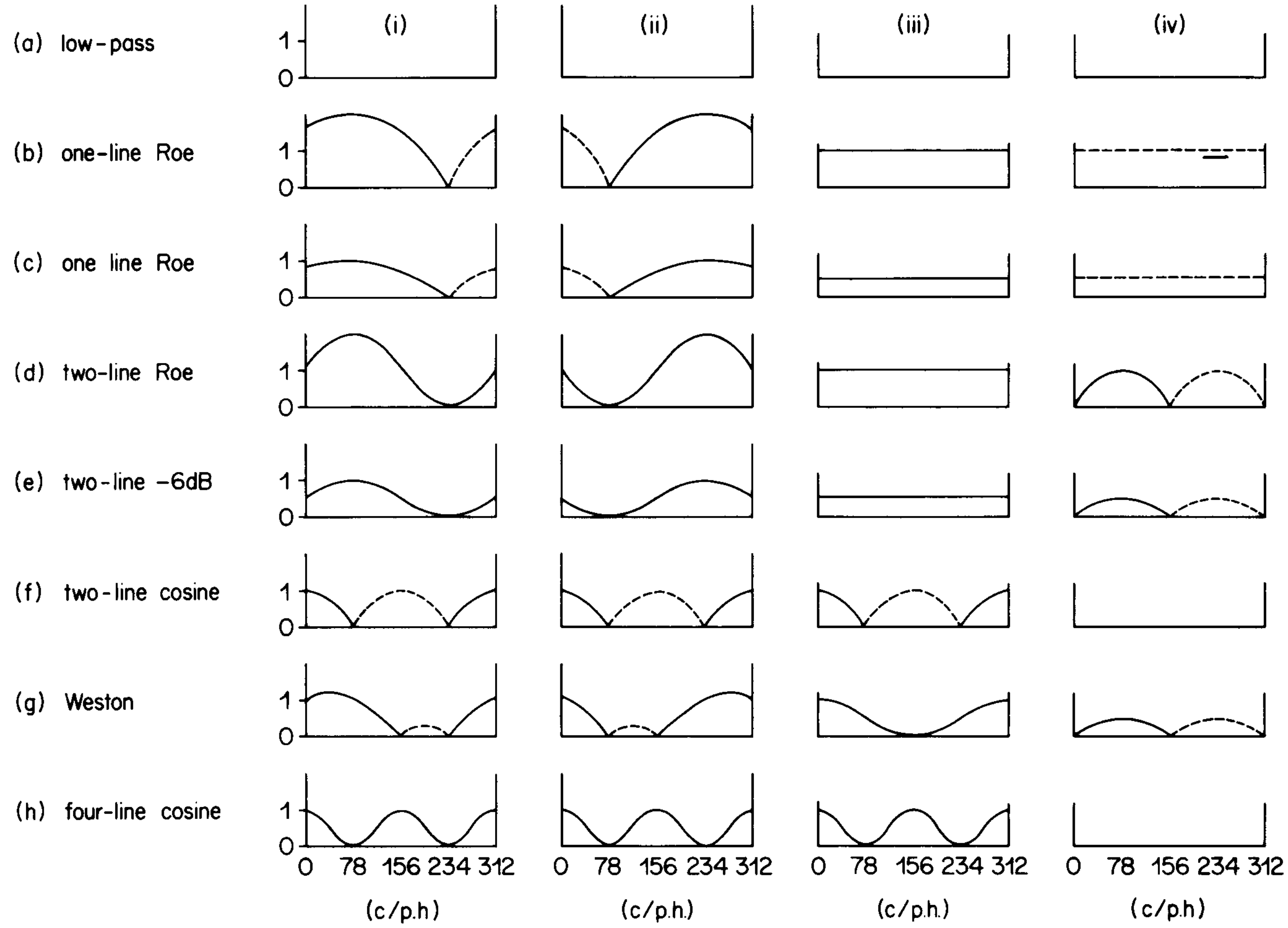


Fig. 12. High frequency luminance vertical frequency characteristics for the decoders of Fig. 10. The four curves for each decoder show: (i) U-phase luminance and cross-luminance, (ii) V-phase luminance and cross-luminance, (iii) true luminance (components unaffected by modifier), and (iv) aliased luminance (components passing through modifier).

3.4.3. One-line −6 dB Roe (Delay Line)

The circuit of Fig. 10(c) is a combination of the previous two circuits, in which co-phased chrominance signals one line apart are averaged. This avoids the possibility of overload produced by the one-line Roe circuit because the amplitudes of true and aliased luminance in the shared band are both halved, so restoring the luminance output to the normal range. Also, the amplitude of cross-luminance remaining at horizontal chrominance transitions (line-to-line changes) is halved as shown in Fig. 12(c), (i) and (ii).

For chrominance, the averaging process sacrifices some vertical resolution in order to suppress Hanover bars. The loss of resolution has the additional effect of reducing cross-colour; for example, (i) and (ii) in Fig. 11(c) show that for line-repetitive signals (0 c/p.h.) such as resolution bars on a test card, the cross-colour is reduced by 3 dB relative to that from a simple decoder. Again, chrominance and luminance are misregistered because the chrominance is, in this case, shifted down the picture by half the spacing between field lines.

3.4.4. Two-line Roe (Two-line subtractor)

Fig. 10(d) shows a development of the one-line circuit, Fig. 10(b), in which a second line delay has been added. Since the phase of both U and V subcarriers is almost exactly inverted over two lines of delay, the two chrominance contributions are averaged by the subtractor before reaching the modifier. As a result, the signals in the modifier path are vertically filtered.

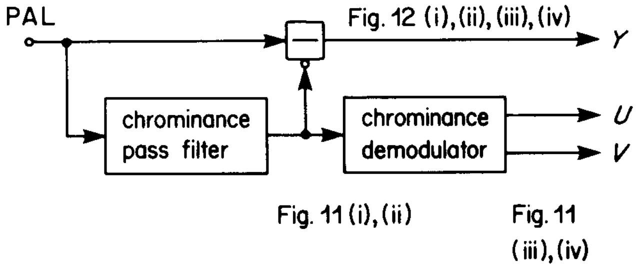


Fig. 13. A general decoder circuit showing the positions of the chrominance and luminance characteristics of Figs. 11 and 12

For luminance signals, this has the advantage that the luminance alias characteristic falls to zero at line and half-line frequency harmonics as shown in Fig. 12(d) (iv). Luminance resolution bars are therefore retained at full amplitude and are free from aliasing. The possibility of overloading is now confined to $\frac{1}{4}$ and $\frac{3}{4}$ line-offset luminance for which the addition of true and aliased components can produce double amplitude signals. However, cross-luminance now extends over two lines on each field at horizontal chrominance transitions.

For chrominance, the addition of the second line-delay has the advantage that there is no vertical misregistration of chrominance and luminance. The loss of vertical chrominance resolution, shown in Fig. 11(d) (iii) is, however, substantial. Also, chrominance at 156 c/p.h. is inverted, so there is no suppression of Hanover bars. Cross-colour is reduced, in particular there is no cross-colour from luminance resolution bars, as shown in Fig. 11(d), (i) and (ii).

3.4.5. Two-line −6 dB Roe (Two-line delay line)

The circuit of Fig. 10(e) is produced by combining equal contributions from the chrominance pass filters of Figs. 10(a) and 10(d). As a result, the chrominance and luminance characteristics of Fig. 10(e) are, in each case, the average of the corresponding curves for Figs. 10(a) and 10(d). Alternatively, the circuit can be considered to be a two-line version of Fig. 10(c).

This avoids the possibility of luminance overranging because the amplitudes of true and aliased luminance are halved throughout the shared band, Figs. 12(e), (iii) and (iv). Consequently, the amplitude of cross-luminance at horizontal colour transitions is also halved, Figs. 12(e), (i) and (ii). Similarly, for chrominance, the loss of vertical resolution is reduced and Hanover bars are suppressed, Fig. 11(e) (iii), but cross-colour returns on luminance resolution bars at an amplitude 6 dB below that for a simple decoder, Fig. 11(e), (i) and (ii).

3.4.6. Two-line cosine

The circuit of Fig. 10(f) shows a method of using signals from adjacent lines without the need for a PAL modifier[3]. Averaging the signals across two line delays tends to cancel the chrominance components, to leave a signal which is predominantly luminance. This luminance signal is subtracted from the coded signal at the centre tap of the line delays to obtain chrominance.

For chrominance, the vertical frequency characteristic, Fig. 11(f), (i) and (ii), is a raised cosine with nulls at the line-offset points and a gain of two at 156 c/p.h. The gain is unity at both the *U* and *V* subcarrier positions. Accordingly, line-repetitive luminance gives no cross-colour, whilst diagonal luminance at 156 c/p.h. gives 6 dB more cross-colour than that from a simple decoder. As the circuit contains no modifier, *U* and *V* signals have the same frequency characteristic.

The demodulation process averages the responses from above and below the subcarrier positions and, in this case, the modulated chrominance characteristic is anti-symmetric about the subcarrier frequencies. Because of this, the characteristics for true chrominance after demodulation are flat, since the falling response from one sideband is neutralised by an equal increase from the other sideband. However, the anti-symmetry introduces crosstalk between the *U* and *V* channels. The *U*–*V* crosstalk characteristic, shown in Fig. 11(f) (iv), has a sinusoidal form with nulls at line and half-line offsets. The mechanism for the crosstalk is that, if the chrominance information changes from line to line, chrominance signals do not cancel in the adder. Then, because these signals are obtained from different lines, without being phase-shifted or modified, the phase of the subcarriers used for the subsequent demodulation is inappropriate. The crosstalk appears as flicker at $12\frac{1}{2}$ Hz on horizontal chrominance edges, such as those in horizontal colour bars.

For high frequency luminance, the circuit produces a cosine characteristic with nulls to suppress subcarrier signals at the quarter and threequarter line-offset points (Fig. 12(f)); diagonal luminance between these points is inverted. Because there is no modifier, the luminance signal is free of aliasing. However, cross-luminance at horizontal chrominance transitions extends over two fields lines, in common with other methods using two line delays.

3.4.7. Weston

When rearranged to the general form of Fig. 1(b), the Weston decoder[2,7] shown in Fig. 10(g), can be seen as a combination of the two-line Roe circuit, Fig. 10(d) and the two-line cosine circuit, Fig. 10(f). In each case, the chrominance and luminance vertical frequency characteristics shown in Figs. 11(g) and 12(g) are the average of those in Figs. 11(d) and 11(f) and in 12(d) and 12(f), respectively.

For chrominance, the Weston circuit introduces a loss of vertical resolution falling to zero at 156 c/p.h. so that Hanover bars are suppressed, Fig. 11(g) (iii). The *U–V* crosstalk characteristic (Fig. 11(g) (iv) has the same form as that for the two-line cosine circuit, but the amplitude is halved. Cross-colour reaches a peak value 1·21 times that for a simple decoder at 5/8ths line offset for *U* and 3/8ths line offset for *V*. There is no cross-colour for line-repetitive luminance, such as test card resolution bars, Figs. 11(g), (i) and (ii).

Similarly, the Weston luminance circuit retains line-repetitive luminance, whilst diagonal luminance at 156 c/p.h. is lost, Fig. 12(g) (iii). The luminance alias, Fig. 12(g) (iv), is half that produced by the two-line Roe circuit and cross-luminance on horizontal chrominance transitions is present on two lines on each field. Phase distorted chrominance signals, which would lead to Hanover bars in a simple PAL decoder, appear at the luminance output of the Weston decoder as a residue of unsuppressed subcarrier signals. This occurs in other methods using PAL modifiers.

3.4.8. Four-line cosine

Using four line delays[6] allows access to lines of the same PAL switch sense, so avoiding both the need for a modifier and the introduction of *U–V* crosstalk. However, there is a serious loss of vertical chrominance and diagonal luminance resolution, Figs. 11(h) and 12(h). In addition, Hanover bars are unsuppressed and cross-luminance at horizontal colour bar transitions extends to four lines on each field.

3.5. Performance comparison

3.5.1. General purpose decoding

The main application of improved decoding is in studios, where access to component signals is needed to simplify signal processing. Under these circumstances, because the signals will be recoded subsequently to PAL, it is an advantage, in principle, to use a complementary decoding method. This avoids the combined gain through the chrominance and luminance channels exceeding unity. However, none of the complementary decoders shown in Fig. 10 has ideal performance, because obtaining good characteristics in one respect usually results in degraded performance in another. In view of this, complementary methods are unlikely to give the best decoded picture quality. So, for other applications, such as improved decoding for receivers, it may be preferable to combine non-complementary luminance and chrominance circuits.

Therefore, first considering the chrominance channels separately, some of the methods are clearly unsuitable for high quality applications. The ordinary delay line PAL circuit using one line delay (Fig. 10(c)), is ruled out by its vertical shift of chrominance information. Also the four-line cosine circuit, Fig. 10(h), has inadequate vertical resolution, falling by 6 dB at only 39 c/p.h. Although the two-line cosine circuit, Fig. 10(f), retains full vertical chrominance resolution, this is at the expense of introducing an objectionable amount of *U–V* crosstalk and substantially increasing cross-colour from diagonal luminance. Neither the simple demodulator, Fig. 10(a), nor the two-line subtractor circuit, Fig. 10(d), suppresses Hanover bars and the two-line subtractor has poor vertical resolution.

The best two circuits for chrominance are the two-line delay line, Fig. 10(e), and the Weston arrangement, Fig. 10(g). The response for true chrominance signals is the same for both of these circuits, with a null at 156 c/p.h. giving suppression of Hanover bars. The loss of vertical chrominance resolution is just noticeable on critical material. The circuits differ, however, in cross-colour and *U–V* crosstalk performance. The Weston circuit has the advantage that line-repetitive luminance, such as test card resolution bars, causes no cross-colour, although rather more cross-colour is produced from diagonal luminance than occurs with the two-line delay line circuit. This slight advantage is outweighed, though, by the disadvantage of *U–V* crosstalk introduced by the Weston circuit on line-to-line chrominance changes. Although this is seldom a problem on real pictures, electronically generated signals, such as horizontal colour bars or electronic test card, suffer considerable impairment; therefore, the two-line delay circuit is generally to be preferred for chrominance.

For luminance, there is a compromise between retaining true luminance and suppressing cross-luminance. Using a lowpass filter, as in Fig. 10(a), satisfactorily removes virtually all cross-luminance, but results in a loss of horizontal resolution and may introduce ringing on luminance edges. All the remaining circuits retain some response in the shared band, but at the same time, suppress cross-luminance in uniformly coloured areas. This is achieved either by using a vertical response with nulls at the subcarrier frequencies (78 and 234 c/p.h.), or by cancellation using modified and phase-shifted chrominance from adjacent lines, or by a combination of both methods.

First considering the Roe methods, Figs. 10(b) to (e), the two-line versions are clearly superior to the one-line circuits because aliasing is reduced, particularly on line-repetitive luminance. The −6 dB version of the two-line circuit avoids the possibility of overloads due to the addition of true and aliased luminance and halves the amplitude of cross-luminance that results from line-to-line chrominance changes. However, the Weston circuit, Fig. 10(g), has an identical aliasing characteristic and a superior response for true luminance; the more important line-repetitive luminance is retained at full amplitude at the expense of diagonal luminance, whereas the Roe circuit of Fig. 10(e) has a uniform −6 dB response at all vertical frequencies.

A disadvantage of all the methods using modifiers is their performance on signals affected by differential phase distortion. This causes the signals derived by phase shifting chrominance from adjacent lines to be no longer in the correct phase to cancel the subcarrier on oppositely-switched lines. As the distortion increases, there is a rapid increase in the level of unsuppressed subcarrier in uniformly coloured areas. When the signals are subsequently recoded, the unsuppressed subcarrier could produce hue errors at the final decoder.

The remaining two-line and four-line cosine circuits do not use modifiers. The four-line circuit, Fig. 10(h) has the disadvantage that cross-luminance at the transitions of horizontal colour bars extends to four lines on each field. The two-line circuit, Fig. 10(f), retains slightly more luminance and, although diagonal patterns are inverted, this is not usually noticeable on pictures. Compared with the Weston circuit, the two-line cosine method produces slightly more cross-luminance, but has no aliasing. The amount of true luminance retained is slightly greater with the two-line cosine circuit, although some frequencies are inverted.

Therefore, a combination of the two-line cosine circuit, Fig. 10(f), for luminance and the two-line delay line circuit, Fig. 10(e), for chrominance gives overall the best decoded picture quality. This is shown in Fig. 14(a). Of the complementary circuits, the Weston decoder, Fig. 10(g), is best although the presence of luminance aliasing and *U*–*V* crosstalk detract from its otherwise good performance. However, none of the methods is likely to give adequate signal quality for recoding to PAL, except for the complementary methods under the special circumstances when the phase of the recoding subcarrier and the *V*-switch sense are the same as those in the first coder.

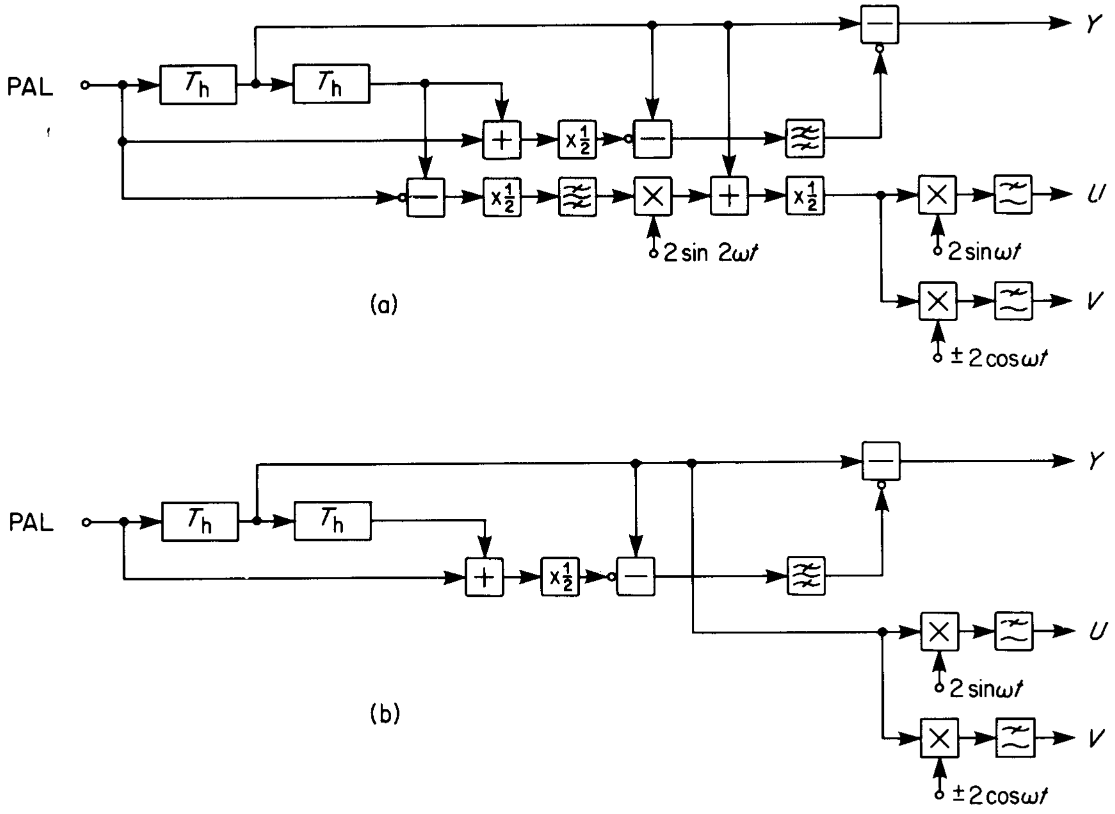


Fig. 14. PAL decoders resulting in (a) the best decoded picture quality for general viewing and (b) the optimum decoding performance for standards conversion

3.5.2. Decoding for standards conversion

The requirements of a decoder for standards conversion are different from those for general use for two reasons: first, the NTSC system can accept only 4·2 MHz of luminance bandwidth; secondly, the interpolation process in a converter acts as a vertical-temporal filter which can be used to suppress unwanted components remaining in the decoded luminance and colour difference signals.

The 4·2 MHz low-pass filter has a beneficial effect on cross-luminance. Any unsuppressed subcarrier signals, such as those at horizontal colour bar transitions, are attenuated by this filter by as much as 6 dB. However, the presence of the luminance low-pass filter reduces the attractiveness of methods using modifiers. This is because some high frequency luminance, ultimately removed by the 4·2 MHz filter, produces aliased frequencies within the filter pass-band. Therefore, the alias, which for PAL was accepted as a necessity for retaining more true luminance, remains in the NTSC output, whilst the true luminance signals are rejected.

The two-line cosine circuit, which has no modifier, gives the best performance for luminance. In addition, this circuit can be used to reduce the amount of cross-colour in the NTSC signal. This is achieved by choosing the luminance combing band-pass filter to have a response of −6 dB near the NTSC subcarrier frequency, so that frequencies which would cause coarse cross-colour on the NTSC standard are combed out before the signal is encoded.

The normal action of the interpolator in a standards converter tends to reduce moving and high vertical frequency patterns, including the cross-luminance and cross-colour left after decoding. When the interpolation method is designed specifically to optimise this action whilst maintaining good picture quality in other respects[4], the interpolator can produce a substantial improvement in picture quality over that of the decoder alone.

Simple demodulation of the PAL chrominance signal is unsuitable for normal use because it fails to suppress Hanover bars and produces more cross-colour than other methods. However, in a standards converter, by using the interpolator to reject Hanover bars and reduce cross-colour, this method of decoding can result in better vertical chrominance resolution than any of the line delay methods.

So the combination of the two-line cosine luminance circuit and simple chrominance demodulation, Fig. 14(b), provides a particularly economical and effective method of decoding PAL in a standards converter.

4. NTSC DECODING

Although PAL and NTSC are broadly similar systems, minor differences in the two signals lead to differences in the two decoders. The NTSC system uses Q and I chrominance components, which are rotated in phase by 33° relative to the $B-Y$ and $R-Y$ colour difference signals. The U and V chrominance components used in PAL are merely scaled versions of the $B-Y$ and $R-Y$ signals, respectively. As the eye is less able to resolve detail for colours along the Q axis, this allows a bandwidth of only 0·5 MHz to be used for the Q signal. A substantially higher bandwidth of 1·3 MHz is used for the I signal, but, because the overall video bandwidth is limited to 4·2 MHz, the modulated I components become asymmetrical centred as they are on the 3·58 MHz subcarrier.

In order to recover U and V components properly from an NTSC signal, it is necessary to demodulate the Q and I signals first, filtering each to its appropriate bandwidth, and then to matrix the resulting signals to give U and V. This arrangement is shown in Fig. 15. It is usual for the I channel of the demodulator to provide some gain for frequencies between 0·5 MHz and 1·3 MHz in order to compensate for the loss of part of the upper sideband. Low-pass filtering of the Q signal is necessary to reject crosstalk from the high frequency components of the I signal. The crosstalk occurs, even though the I and Q signals were originally in quadrature, because of the asymmetry in the sidebands of the I signal.

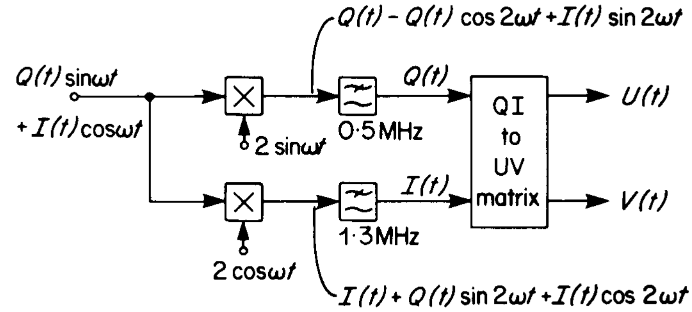


Fig. 15. An NTSC chrominance demodulator

A further difference arises from the spectral positioning of the subcarriers in the two systems. To minimise crosstalk with luminance, these must be located away from the main luminance components, which are situated at and around harmonics of line frequency. The PAL subcarrier has an approximately three-quarter line offset to accommodate the half-line rate switching of the *V* component. So the *U* and *V* modulated components are located at the three-quarter and quarter line offset positions, respectively. In the NTSC system, however, both chrominance components have a half-line offset from the main luminance components. This greater separation of luminance and chrominance in the NTSC system allows comb filtering methods to be used which are simpler and, at the same time, more effective than those used for PAL. This simplifies the choice of comb filtering options in NTSC.

Only two circuits, therefore, are of any interest for NTSC chrominance–luminance separation. These are, first, the low-pass filtering of luminance with simple demodulation of chrominance and, secondly, the use of a two-line comb filter. Although one-line circuits can be used, these result in a shift of luminance and chrominance down the picture by half the spacing between field lines.

4.1. Low-pass (Simple)

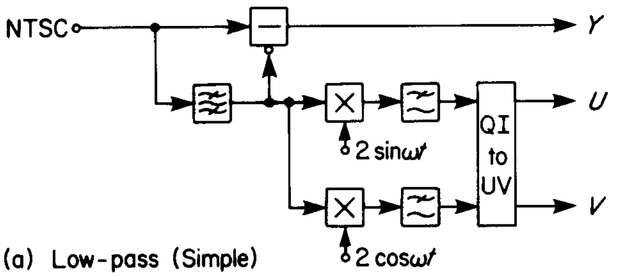
Although the NTSC signal can be split by treating all the high frequencies as chrominance and using only the low frequency components for luminance (Fig. 16(a)), the results are less effective than those obtained by this method for PAL. The subcarrier signals (cross-luminance) are effectively suppressed, but because of the lower luminance bandwidth (4·2 MHz) and lower subcarrier frequency (3·58 MHz) of system M signals, the loss of luminance resolution becomes more serious with very little energy remaining above 2 MHz. For chrominance, there is no suppression of cross-colour.

Vertical frequency characteristics for this decoder are shown in Fig. 17(a) for chrominance and 18(a) for high frequency luminance.

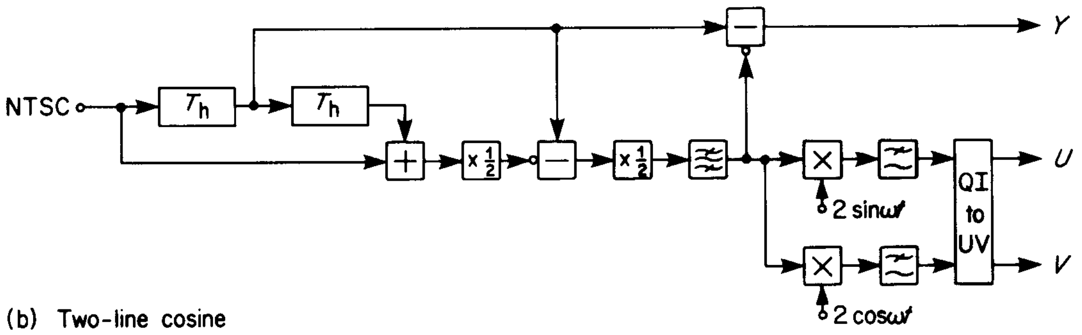
4.2. Two-line cosine

By using a vertical filter an increase in horizontal luminance resolution can be obtained at the expense of some vertical chrominance resolution. The most frequently used arrangement is shown in Fig. 16(b). With NTSC signals, the subcarriers are both co-phased across a delay of two line periods. Thus, when these signals are averaged and subtracted from the anti-phased signals at the mid-point of the delays, line-repetitive luminance is cancelled and the chrominance remains. After band-pass filtering, the separated chrominance signal is subtracted from the composite signal to leave luminance.

The increased luminance resolution gives a substantial improvement in quality over low-pass filtering. However, a slight drawback is the reappearance of cross-luminance on vertical chrominance detail, such as at the transitions of horizontal colour bars. For chrominance, the loss of vertical



(a) Low-pass (Simple)



(b) Two-line cosine

Fig. 16. NTSC decoder circuits

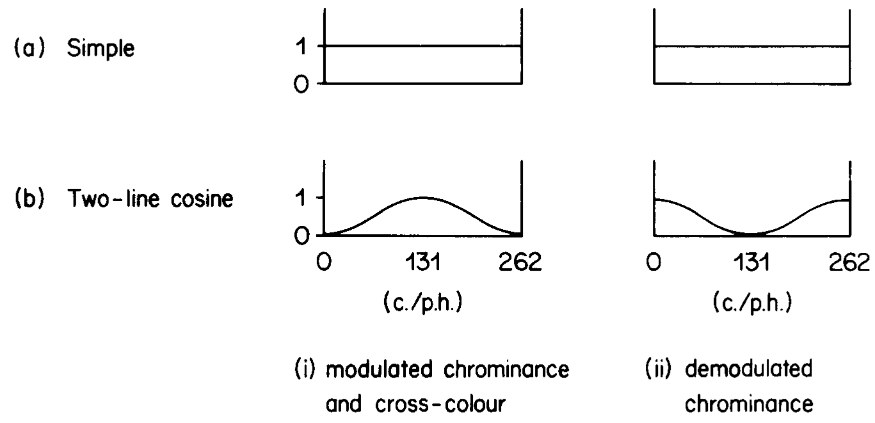


Fig. 17. Chrominance vertical frequency characteristics for the decoders of Fig. 16. The two curves for each decoder show I and Q cross-colour and demodulated chrominance resolution

resolution is rarely noticeable and is more than offset by the elimination of cross-colour from line-repetitive luminance. The chrominance and luminance characteristics for this circuit are given in Figs. 17(b) and 18(b).

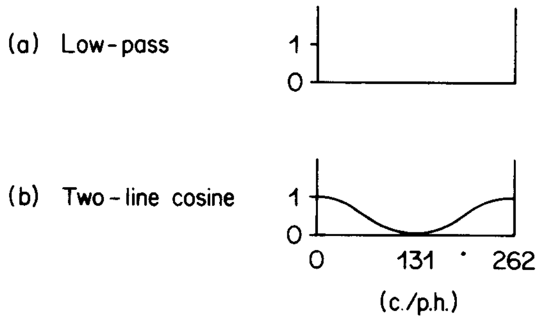


Fig. 18. High frequency luminance vertical frequency characteristics for the decoders of Fig. 16

4.3. Performance comparison

For general use, the two-line cosine filter gives good results, with the presence of unsuppressed cross-luminance on horizontal colour transitions being the main disadvantage.

For standards conversion, it was found advantageous to use a combination of the two-line cosine circuit for luminance and simple demodulation for chrominance, as shown in Fig. 19. The temporal and vertical filtering action of the interpolator has a beneficial effect, as for PAL, on the cross-colour and cross-luminance components left by decoding. Thus the moving cross-luminance left at horizontal colour bar transitions was less noticeable after the conversion process than it was at the decoder output. Similarly, moving cross-colour was suppressed much more effectively than by the vertical filter in the decoder. So, by omitting the vertical filter for chrominance, it was possible to retain much more vertical resolution without cross-colour becoming a problem.

5. CONCLUSIONS

At the outset of the work, many new forms of PAL decoder had been suggested for a variety of applications. Whilst some employed familiar analogue circuitry, the majority made use of digital techniques to obtain improved accuracy and stability. Of these methods, several required the digital samples to be taken at particular phases relative to the colour subcarrier and others depended on the sampling rate being locked to the line frequency. The circuit arrangements of the digital decoders bore little resemblance to those of conventional analogue decoders.

After closer examination, however, it was

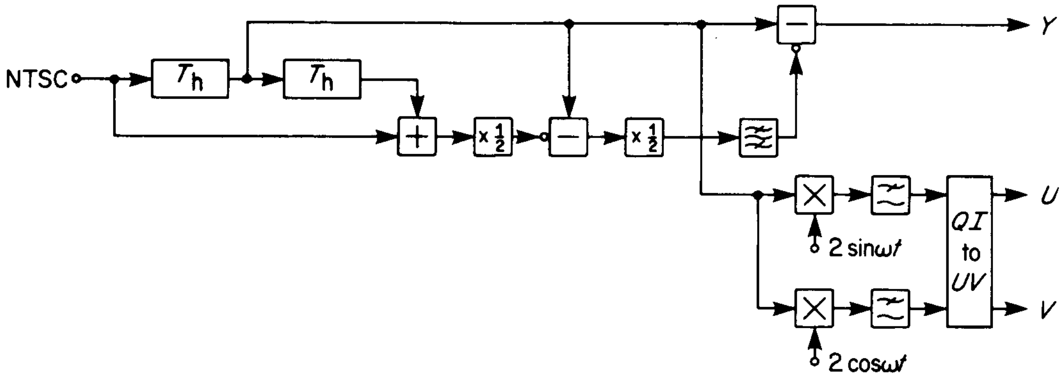


Fig. 19. The optimum form of NTSC decoder for standards conversion

apparent that the effect of the chrominance demodulation process was equivalent in every method to that of synchronous demodulation. In this respect, the action of the different decoders was, in principle, the same regardless of whether the method was implemented with analogue or digital circuits, or with different sampling frequencies. Consequently, neglecting practical differences arising from the use of analogue or digital technologies, the only significant difference between any of the decoding methods was in the action of the filters used to separate chrominance and luminance.

It has proved possible, therefore, to convert all the previously known decoding methods into equivalent circuits of a more general form. In this form, the differences between the methods of comb filtering are more apparent, so that the performance parameters of the circuits can be summarised and compared more easily. Moreover, each of these generalised methods can be applied either using line- or subcarrier-locked sampling, or with analogue circuitry, without any dependence on the techniques used when the method was originally devised.

The interpolation process of a digital standards converter is simplified when line-locked sampled luminance and colour difference signals are used. Suitably sampled signals can be obtained directly by using line-locked sampling in the decoder as well, although the complexity of the demodulator is marginally increased over subcarrier-locked methods. This form of digital decoding proved very effective for comparing the performance of different comb filter arrangements, as the system was free from the unwanted parameter variations often associated with analogue equipment. The digital demodulation process did not introduce any observable patterning or quantising effects. Intermodulation products introduced by the analogue-to-digital conversion process could be detected, but these are maintained at an acceptably low level with current designs of a–d converter.

The various comb filter arrangements represent different methods of dividing the video spectrum into luminance and chrominance regions and, therefore, each is a different compromise between retaining resolution and minimising cross-effects. The performance of each filter has been summarised as a series of vertical frequency characteristics describing the luminance and chrominance resolution, the susceptibility to cross-luminance and cross-colour, and the occurrence of luminance aliasing and U–V crosstalk.

Of the many forms of filter tested for PAL and NTSC, none gave completely satisfactory results. For general use, the combination of the two-line cosine luminance circuit with the two-line delay line chrominance circuit (Fig. 14(a)), a non-complementary method, was found to give the most acceptable picture quality for direct viewing. However, the Weston circuit (Fig. 10(g)) was found to be the best complementary method and, therefore, the most suitable for situations in which the decoded signals are to be recoded subsequently to PAL. Nevertheless, it appears unlikely that any method of PAL decoding using line delay comb filters will give adequate separation of luminance and chrominance to be used satisfactorily as an input to component signal processing equipment in studios.

For such applications, in which recoding on the same standard is envisaged, the use of field or picture stores in the decoder[6,9] can improve performance on still and slowly moving pictures. However, these decoders give serious impairments on rapidly moving coloured areas of picture. The production of a high quality decoder for studio processing therefore depends on the development of an effective movement detector to adapt the decoder to a line-based method in areas of rapid movement.

Fortunately, in a standards converter, the interpolation process acts as a vertical-temporal filter. This provides additional suppression of the predominantly high vertical and temporal frequencies of chrominance and luminance cross-effects left by the decoder. Also the interpolator can suppress Hanover bars without loss of vertical resolution. It was particularly noticeable that the additional impairments, such as luminance aliasing and U–V crosstalk introduced by some decoding methods, were more disturbing than the resolution loss suffered with other methods. For standards conversion, therefore, the optimum decoding arrangements, both for PAL and NTSC, were found to be the two-line cosine luminance comb filter and simple, unfiltered demodulation of the chrominance (Fig. 14(b) and Fig. 19). Then, the levels of cross-colour and cross-luminance present in the component signals after standards conversion were substantially lower than those present in conventionally decoded signals; at the same time, the converted signals maintained higher spatial resolution. In addition, the effect of filtering in the decoder and interpolator was similar to that of prefiltering in a "clean" coder[9], acting to reduce cross-effects in the output standard coding system. The output signals were, therefore, of high quality, relatively free from the cross-effects of the input and output standards.

Analogue versions of the methods of PAL and NTSC decoding recommended here have been used in the two production standard converters, known as ACE*, made for the Television Service by Designs Department.

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*ACE – Advanced Conversion Equipment. ACE is being manufactured for general sale by GEC-McMichael Ltd.